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MODELING

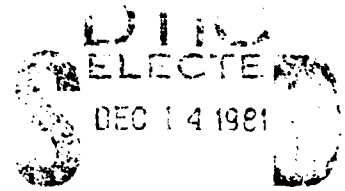HUMAN ATTENTION ALLOCATION STRATEGIES

IN SITUATIONS WITH COMPETING CRITERIA

Final Report

March 1981 - August 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
In supervisory control situations involving multiple human operators, proper co-operation and coordination is essential. In addition to their individual tasks, the operators are jointly responsible for certain tasks. It is usually not clear when and who should take responsibility for the joint tasks. Proper scheduling of tasks and appropriate allocation of resources are necessary for optimal per-formance, and in some instances, for overall safety. Understanding how multiple operators interact requires the understanding of single operator performance. A model based on Pareto Optimality and Fuzzy Set theory was developed for the human

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20. operator. An experimental paradigm had been developed earlier to study the human monitor. The scenario used was similar to monitoring the spread of forest fires, and timely identification of threatening conditions. Experiments were conducted based on the paradigm. Results showed that the operators used updates to reduce the uncertainty to a sufficiently low level before starting threat classification. Sites where the probability of damage was close to 0.5 were more difficult to classify. Early decisions resulted in more errors. Heuristics proposed earlier appeared to be relevant

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INTRODUCTION

In certain Command, Control, and Communication (C^3) environments, a number of human operators function as a group to achieve some desired objective. They are usually aided by computers and other automated systems. In such supervisory control problems proper coordination is necessary for successful operation. It is not always clear how and when various functions must be allocated to different operators.

Certain operations require some specific type of attention (and action by the human) and are allocated to a particular individual. But there are also a number of operations that do not fall within the domain of a particular operator. Two or more operators may be jointly responsible. Depending upon the relative workload levels at any particular point in time, one of the operators jointly responsible will perform the task. The objective here is to understand the nature of attention allocation and task sharing responsibilities when multiple entities are responsible for system operation.

As a first step, this requires an understanding of how one individual might act in an environment where his attention must be allocated between a number of competing systems, or where a number of performance criteria are conflicting. Due to the cooperative nature of the problem (since the operator wants to optimize all the elements of the vector of performance indices) the appropriate solution might be to find the Pareto optimal set of solutions.

The Pareto optimal set is then reduced to a single preferred solution by the use of heuristics or other relevant information employed by the human operator. Desirability indices for various alternative actions can be found using fuzzy set theory. The particular control strategy having the highest value for this desirability index can then be implemented. A model for the human has been proposed earlier [1,2] that incorporates the above features. Experiments that take into account the above characteristics are needed to validate the model and/or refine it if necessary.

OBJECTIVES

An experimental paradigm was developed for a threat assessment scenario, based on monitoring the spread of forest fires. Fires originated from five sites and spread outward. Certain areas were more valuable than others, and were denoted as protected zones (PZ). These were shown as circular arcs [1,2]. The envelope within which the path of the fire was expected to lie was indicated by fans emanating from the sites. More accurate information about the path of the fire was available as time progressed. The subjects could update these at any time. Decisions concerning threat were to be made before a certain time limit. Experiments were conducted where a number of human operators participated. Complete details are given in [1].

As the subjects performed the experiments, data were collected about the decisions made by the operators, and the times at which the decisions were made. These included updates as well as threat classification. The primary objective of the mini-grant has been to analyse the experimental

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results for modeling purposes. In particular, the following objectives were desired.

(1) Identification of the heuristics and strategies used by the human operator.

(2) Comparison of experimental results of various operators for the purpose of identifying the decision making strategies.

(3) Preliminary verification of the model structure with regard to the appropriateness of the use of various heuristics.

(4) Study of possible alternatives for the model structure, and modifications of the experiment for further research in modeling.

STATUS OF THE RESEARCH

As a means of achieving these objectives, computer programs were written to analyze the experimental data. Using the data, the programs "recreated" the experimental conditions when the subjects made decisions concerning threat. This enabled us to determine the exact configurations at the time of the decision. In particular, the probability of damage (p_d) and the positions of the fans with respect to the protected zones were evaluated. The programs were fairly complex since the exact configurations were required. Modules from the program that was used in the experiments simplified the programming effort somewhat.

Analysis of the data was carried out to identify the operator's strategies. Since a large amount of data have been collected, the analysis has not been completed. Certain major trends were apparent from the analysis thus far completed. A brief summary of the results is given here.

The subjects cycled through the sites in a more or less sequential order when there was a lot of time available. After about two or three cycles, the subjects started to investigate specific sites. Easy identifications were completed before going on to more difficult (i.e., uncertain) sites. More updates were required for difficult sites. Sites where the probability of damage was near 0.5 proved to be more difficult than the extreme cases (i.e., p_d close to 0.0 or 1.0). This agrees with what one would expect intuitively. There was a strong tendency to identify the sites with p_d near 0.5 as threats. Details can be found in [2].

In general, most of the heuristics proposed earlier seem reasonable. Formulation of appropriate fuzzy relationships is necessary to test the degree of applicability of the rules. A major observation is that there are two distinct phases in the operation of threat identification. During the first phase, uncertainties of all the sites are reduced to a sufficiently low level by cycling through all the sites. This phase is quite straightforward, and does not seem to impose any unusual decision making loads. During the second phase, the human generates a set of alternatives from which a single site is chosen for update and/or threat classification. Decision concerning threat is made from the estimated value of the probability of damage. Errors in identification were higher when decisions concerning threat were made early. There was perhaps no "Uncertainty Reduction" phase in such cases.

A crucial point in the development of the model is the determination of when the subject switches from the initial "Uncertainty Reduction" phase to the "Threat Classification" phase. This is expected to be a function of

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the time remaining, as well as the perceived probabilities of damage. Detailed analysis is needed to study this problem further.

During trials, certain sites were more error-prone than others. These must be studied separately. Detailed configurations corresponding to these sites might reveal some features not anticipated in modeling. Also, the order in which sites were classified could reveal some configurational bias. Individual variations can be taken into account in the model by appropriately varying the fuzzy relationships. All these features will be studied in detail later.

SUMMARY

Experiments involving decision making in a time-constrained environment were completed. Results of the preliminary data analysis indicate that the human operator might be using subjective criteria after the initial uncertainty has been reduced to a sufficiently low level.

The heuristics proposed appear to be reasonable. Testing of these and identification of additional heuristics and rules can only be performed after additional modeling effort. This would be possible after the appropriate fuzzy relationships are developed based on various heuristics.

Alternate modeling techniques are also being explored. In particular, Semi-Markov Decision Processes and Artificial Intelligence techniques appear to be attractive. Another possibility is to study this as a Closed Queueing Network problem with time varying arrival time statistics. A formal research proposal is being prepared based on the results of the research

conducted during the duration of the mini-grant. The proposal will be submitted to the Air Force Office of Scientific Research in the near future.

LIST OF PUBLICATIONS

[1] Govindaraj, T., Poturalski, Capt R. J., Vikmanis, M. M., and Ward, S. L.: "Human Attention Allocation Strategies in Situations with Competing Criteria - Development of an Experimental Paradigm and Outlines for a Model", Preprints of the Eighth Triennial World Congress of the International Federation of Automatic Control, Kyoto, Japan, August 24-28, 1981.

[2] Govindaraj, T., Poturalski, Capt R. J., Vikmanis, M. M., and Ward, S. L.: "A Model for Human Attention Allocation Strategies in Situations with Competing Criteria", Proceedings of the 1981 International Conference on Cybernetics and Society, October 25-28, Atlanta, Georgia.

ASSOCIATED PERSONNEL

Dr. Thiruvenkatasamy Govindaraj

INTERACTIONS

Results of the research were presented in August 1981 at the Eighth Triennial World Congress of the International Federation of Automatic Control in Kyoto, Japan, and at the 1981 International Conference on Cybernetics and Society in Atlanta, Georgia in October. These conference papers are included as Appendices 1 and 2 respectively.

The experiments were developed during the summer of 1980 under AFOSR Contract F49620-79-C-0038. (The principal investigator was an AFOSR Summer Faculty Research Associate at the Air Force Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base.) Modifications of the experimental procedures were carried out during the fall of 1980. Experiments were completed *prior to the* grant period at AFAMRL. Captain Richard J. Poturalski, Maris M. Vikmanis, and Sharon L. Ward of the Technology Development Branch (Human Engineering Division) conducted the experiment. They also participated in the preparation of the conference papers, and in consultations during various stages of modeling by providing useful comments and valuable suggestions.

75.3   Appendix 1

HUMAN ATTENTION ALLOCATION STRATEGIES IN SITUATIONS WITH COMPETING CRITERIA

- DEVELOPMENT OF AN EXPERIMENTAL PARADIGM AND OUTLINES FOR A MODEL

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Abstract. In supervisory control situations involving multiple human opera-
tors, proper cooperation and coordination among the operators is essential.
In addition to their individual responsibilities, the operators are jointly
responsible for certain aspects of the system. Time available for decisions
may be limited, and various criteria may conflict with each other. Proper
scheduling of tasks is necessary for optimal performance. In such situa-
tions it is usually not clear when and who should take responsibility for
the joint tasks. Understanding how multiple operators interact requires the
understanding of single operator performance. A model based on Pareto op-
timality and fuzzy set theory has been proposed for the human operator. An
experimental paradigm has been developed based on a threat assessment situa-
tion. Features of the paradigm are explained. A detailed outline for the
model structure is given, and experimental results are discussed.

Keywords. Man-machine systems; Air traffic control; Cognitive systems; De-
cision theory; Game theory; Optimal systems; Applications of fuzzy set
theory.

INTRODUCTION

In certain Command, Control, and Communica-
tion (C^3) situations, a number of human
operators function as a group to achieve
some desired objective. In their efforts to
perform their work they are aided by comput-
ers and other automated systems. In such
systems, the human operator is more of a su-
pervisor than a simple controller. In super-
visory control where more than a single
operator is involved, proper coordination is
necessary for successful operation. Among
other things, a need for more than one per-
son is necessary due to the increased com-
plexity of the systems that dictate various
kinds of expertise, as well as the mere
number of components involved. In such sys-
tems, more often than not, allocation of
various functions to different operators is
not usually clearly defined.

Of course, there are certain operations in
each of the various subsystems that require
some specific type of attention (and action
by the human) and are allocated to a partic-
ular individual. But there are also a number
of operations that are not clearly definable
as falling within the domain of a particular
operator. Two or more operators may be
jointly responsible for the functions.
Depending upon the relative workload levels
at any particular point in time, one of the
operators jointly responsible will take
responsibility. In general, computers when
working with the human can be used to per-
form some of the functions. It is our desire
to understand the nature of attention allo-
cation and task sharing responsibilities
when multiple entities are responsible for
the operation.

We need to understand how different entities
work together in a cooperative environment
to share responsibilities. As a first step,
this requires an understanding of how one
individual might act in an environment where
his attention needs to be allocated between
a number of competing systems or where a
number of performance criteria are conflict-
ing. Though a number of mathematical models
have been proposed for multiple task
sequencing by a single operator, (Rouse,
1977; Krishna-Rao and others, 1980), they
are not applicable for our problem. Our
problem has the important characteristic
that multiple performance criteria are in-
volved. The criteria are distinctly dif-
ferent from each other, and cannot simply be
added to obtain a single performance index.

Satisfaction of a particular criterion might
require some specific action that might con-
flict with another action dictated by the
need or desire to satisfy another criterion.
In an actual situation there may be more

than two criteria that must be satisfied simultaneously. By satisfaction of a criterion is meant taking an action that would produce optimum results if that criterion alone were to be considered. In practical situations, compromises are often made so that instead of optimizing a single performance criterion, a number of criteria are optimized simultaneously. Since the various criteria are in general not additive, they must be considered as elements of a vector. Due to the cooperative nature of the problem (since the operator wants to optimize all the elements of the vector) the appropriate solution might be to find the Pareto optimal set of solutions. These are the non-dominating set of actions, no single action being more preferable to any other in the absence of additional information or constraints.

When a human operator is involved, he uses his experience and various biases to reduce the set of solutions to a single solution to be used at any particular choice point. Hence the Pareto optimal set is reduced to a single preferred solution by the use of heuristics or other relevant information (see Govindaraj, 1980). In man-machine systems, the human operator's heuristics are better expressed in terms of suitable linguistic expressions. Since we need to quantify the variables expressed linguistically into a form usable when the information from the system is in terms of numbers, the most appropriate method appears to be via the fuzzy Set theory. Various heuristics and rules used by the human can be used to define the appropriate relationships between the different entities that make up the overall system. The Pareto optimal solution set can be generated and various control strategies can be assigned appropriate "desirability indices" based on the rules. The particular control strategy having the highest value for this desirability index (membership function in fuzzy sets) can then be implemented. Certain features in the development of the model closely follow Zadeh (1976).

OBJECTIVES

The fundamental problem of interest concerns development of an appropriate paradigm for studying the human operator characteristics discussed above. In particular, a good understanding of the features of the problem/environment that are useful to the human in arriving at decisions to be implemented is desired. Possible heuristics and strategies that the human uses to reduce the size of the feasible set of solutions must be identified. Hence, the experimental paradigm must incorporate the relevant features of the environment, without making it overly complicated that it becomes impossible to isolate the various factors in-

volved. It should also be possible to vary different parameters so that the effects of different paramters can be studied. The experimental paradigm is set up with the aim of modeling the human, using Pareto optimality and Fuzzy Set Theory. Research currently in progress towards realization of these objectives is described in the following sections.

AN EXPERIMENTAL PARADIGM

A typical situation that has the characteristics of interest is the monitoring of the spread of forest fires that occur during summer. This threat assessment scenario is simplified somewhat to make the problem tractable. The essential characteristics have been retained. Since the primary aim of this work is to evaluate the possibility and suitability of modeling using the techniques discussed earlier, the details of the problem are not crucial as long as the essential factors are taken into account. Details of the problem can be better understood with reference to Fig. 1. The main features are the number of points at which fires have originated ("sites"), from which fires could spread to other areas in the forest. Certain areas in the forest (or on the fringes) are more valuable than others, for example, due to housing and/or other property. These are called Protected Zones (PZ) and are indicated as circular arcs in the figure. The number of locations at which fires can start has been fixed at 5 for our experiment. The operator must determine from the information displayed on the screen whether the sites pose a threat to the protected zones. A limited amount of time is available to make this decision. This time is taken to be between two and three minutes. (In practice, threats must be identified in a few hours, and the available resources must be allocated optimally.) Mistakes in making proper decisions are expensive. There are two types of mistakes: declaring that a site is a threat when it is not a threat, and declaring that a site is not a threat when it is really a threat. The operator makes this decision based on the information available on the screen.

The angular envelope within which the trajectory is expected to lie is indicated by a fan. The fan provides the 95% confidence interval for the trajectory. Within this fan, 95% confidence interval for the expected range is indicated by the dotted lines. The envelopes displayed on the screen are based on the estimate of the information available at the time the display was originally drawn. As time progresses more accurate information becomes available for each site, but it is not displayed automatically. At any time the operator has the option of asking for more information concerning any particular site. Since it takes a certain

amount of time to obtain the required information from a site, and since the total time available within which the decision must be made is limited, proper scheduling is very important.

A line perpendicular to the center line of the fan gives an indication of the estimated position of the fire-front with reference to the starting location. This line is continuously updated, based on the assumption that the velocity of the front is known. Even though the direction of the center line may change with time, the front position line moves along the center line corresponding to the last update. This line is the only direct indication of the elapsed time. The operator gets an estimate of the remaining time from observing the position of this line.

At any point in time the operator can decide if a particular site is a threat or not a threat, or can continue to monitor in the hope of obtaining more reliable information later. Better quality information can be obtained by requesting for additional information at any time. Since the initial information is rather crude, the rate of improvement in the quality of the information is greater in the beginning. This, along with the fact that more time is available to make the final decision, might encourage the operator to ask for more information in the beginning. However, as time goes by, the pressure to classify a site increases because appropriate action must be taken if it is a threat. Hence, the identification of threat is made taking into effect all these factors.
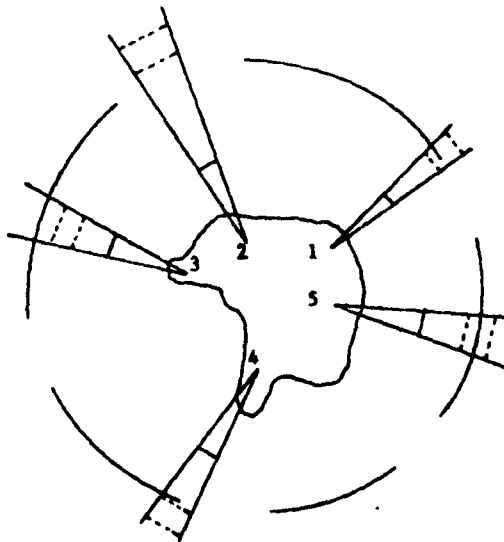
EXPERIMENTAL DETAILS

In our experiment, at the beginning of the trial fires start from all five sites. In a more realistic scenario, fires from different sites might start at different times. In fact, we do not know how many distinct fires start in a forest. Our objective is to understand how decisions are made when there are conflicting criteria. It is desirable to avoid factors not directly related to the basic problem. Hence, it is adequate to start all the fires simultaneously. The subject can update any site merely by typing the site number. In a real life situation, updating information takes some time. This reflects processes such as calling up a source of information, obtaining relevant information, processing it, and updating the display. In our experiment this is done by freezing the display for 5 seconds. When the subject requests an update for a particular site, a message appears indicating that the requested site is being updated, and after 5 seconds, the 95% confidence intervals are updated. When the nature of threat is identified for a site, i.e., a decision is made, that site is removed from the display. The experiment proceeds until all the sites have been identified or until a pre-determined time limit, whichever occurs first.

The experiment has been run in real time on a PDP 11/34 computer using the VT11 Graphics system. Initial training runs were conducted for a week to familiarize the subjects with the experiment. During this period the subjects were expected to develop a set of consistent strategies for decisions. The subjects were encouraged to avoid making errors of any type. A score based on the correctness of the decision concerning threat and the quickness in making the correct decision was calculated for each site. The score for a site is the time remaining at the time the decision was made. At the end, the display was redrawn to indicate the final configurations of the confidence intervals, and the scores were displayed. Incorrect identifications were shown by flashing the confidence intervals and giving zero scores. This form of feedback was provided during the data runs as well.

A number of different experimental conditions characterized by different configurations of the fans were used. The configurations differed in terms of the area of overlap of the uncertainty envelopes with the protected zones. This represented different levels of threat probability. Ten configurations for each of the 10 sessions were used. For a particular session, the order of presentation was randomized.

Fig. 1. Threat assessment scenario

PROPOSED OUTLINE FOR THE MODEL

The operator functions in an environment where a set of criteria, not necessarily commensurable, must be simultaneously satisfied for optimum performance. The information the operator has about the system can be divided into two main categories. One is the information concerning the Predicted End Point (PEP) at which the fire is extinguished. The PEP is shown by the width of the fan and the dotted lines indicating the range. In addition, an indication of the actual range of the fire is available from the front position line. The other information is the perceived probability of damage to the protected zone, p_d, given by the relative size of the area of overlap of the PZ and the confidence interval. These are related to each other, and the human decides on a particular action based on the above and the time available.

The threat assessment for this situation consists of assessing the potential threat from each of the individual sites. If it is possible to eliminate some of the sites from further consideration, i.e., by deciding if they are threats or no-threats early in the cycle, more time is available to decide on the remaining sites. To set up the cost functionals for the problem each site will be assigned a set of costs. For any site the uncertainty/pressure associated with elapsed time (or equivalently time remaining for making the decision) will form one of the costs (J_{i1} for the ith site). The other cost is the amount of uncertainty associated with PEP. This latter cost could be directly related to the area of the region of uncertainty associated with PEP. For site i, the costs are (J_{i1}, J_{i2}). J_{i1}, the cost associated with the time uncertainty increases continuously with time. In addition, a certain amount of fixed cost should perhaps be added whenever new information is requested, reflecting the fact that some time is lost in that process.

The control action consists of the determination of which site to investigate at any particular time. This could be done by scheduling two or more sites to be investigated consecutively. Depending upon the uncertainty, in general, one could request information concerning the range (the linear dimension) and/or the fan width for PEP. (In our experiment both of these are updated, though it is possible to update only one.) The general form of control vector is given by

$$u' = (t_1, t_2, \ldots,) \tag{1}$$

where t_i is the time at which site i is to be updated. The perceived probability of damage, p_d, is given by,

$$p_d = p_d(t, F_p, R_p, PZ) \tag{2}$$

where the subscript p denotes the perceived

values, and F and R are the fan width and range respectively. At any point in time, the human might possibly be ranking the various sites in order of importance as potential threats and decide on the appropriate action. The number of sites (actively) competing for action as well as the time remaining will influence the control.

For making decisions concerning the nature of the threat, the human estimates a number of quantities, such as the time remaining, positions of the fire-fronts, and the regions of uncertainty. The estimation problem is a difficult one because the operator has no control over the fires' propagation. The parameters influencing their propogation are not known. Hence, identification of the parameters is necessary for the estimation problem. When the uncertainty envelopes are updated, the information gained could be used for the identification. The values of the parameters thus identified could be used for estimating the variables between updates.

From the estimates of various quantities thus obtained, a set of alternative solutions is generated. Methods of generating this Pareto optimal set are being explored. Heuristics and other information concerning the threat assessment problem are formalized using fuzzy set theory. Fuzzy relationships developed from these are used to reduce this Pareto optimal set to a single alternative. Figure 2 shows a schematic block diagram for the operator model. It should be noted that the identification block gets an input only when there is an information update. When a decision is made concerning threat or when the operator is uncertain, and after information updates the cycle restarts at the estimation block. The arrow from the identification block to the estimation block represents the transfer of parameters. Detailed structures for the various blocks are being worked out.
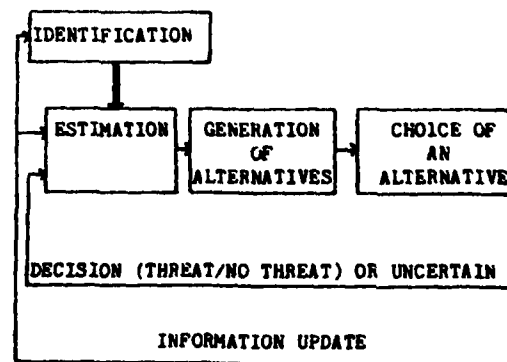

Fig. 2. Schematic block diagram of the model

Appropriate "desirability indices" must be associated with various controls that form the Pareto optimal set. Rules and heuristics that might be used by the human need to be identified for this purpose. Examples of some possible heuristics are given below.

1. Do not ask for information from the same site consecutively, unless that site could be eliminated from further consideration.

2. After each enquiry for additional information, p_d is updated and used to decide on the next action. If p_d exceeds an upper limit p_{hi}, the site is classified as a threat, and if p_d falls below a lower limit p_{lo}, the site is classified as a non-threat. (Otherwise a decision is postponed due to uncertainty.)

3. If the time available is decreasing, and the number of sites is large, the no-decision range ($p_{hi} - p_{lo}$), is reduced. This reduction could occur after each update or it could be a continuous function of time. The reduction could be achieved by lowering p_{hi}, raising p_{lo}, or by changing both.

4. If damage probabilities are "about equal" for two sites, the tendency would be to update the site having the higher uncertainty.

5. For two sites having "nearly equal" p_d values, choose the site having the value closer to the decision boundary (i.e., near p_{hi} or p_{lo}).

6. If p_d for site i is closer to p_{hi}, and p_d for site j is closer to p_{lo}, choose site i (potential threat is more important than a non-threat).

7. In trying to reduce the uncertainty associated with a PEP, if the reduction in one dimension is greater than in the other dimension, choose the control that would result in maximum expected reduction.

8. The uncertainty, and hence the tendency to classify a site as a threat, increases as the PEP goes closer to the PZ.

9. If two fire-fronts propagate with different velocities, the front with the faster velocity is more of a threat. This reflects the faster rate of reduction of the available time for the faster front.

10. After the "desirability membership function" values are calculated, the control is not implemented if the value of this function falls below a certain threshold. The action is to continue monitoring.

This list is by no means complete. Validity and/or relevance of the various rules can only be tested by matching the model results with the experimental results. Unlike the direct problem where known set of heuristics are used in various fuzzy relationships, we need to identify proper heuristics and stra-tegies by matching results. Hence, this is in effect an inverse problem, an important distinction to be noted.

EXPERIMENTAL RESULTS

Experiments have recently been completed. Detailed analysis of the results are being carried out. Only a few of the important observations will be given here. A thorough analysis must wait the later stages of the modeling process. The subjects cycled through the sites in a more or less sequential order, in the beginning, when a lot of time was available. After about two or three cycles, the subjects started investigating specific sites. Easy identifications were completed before going on to more difficult or uncertain sites. Difficult sites required more updates. In most cases, almost all the subjects had a tendency to identify the uncertain sites with about 50% probability of damage as threats.

Another interesting observation was that often the subjects declared a site a threat if, after an update, the "fan" moved towards the Protected Zone. The subjects could be using some form of a predictor. The model could include this as a dynamic system driven by a noise. The driving noise characteristics must be determined by the model.

POSSIBLE APPLICATIONS

In addition to its use in the monitoring situation considered here, the model could be useful in a number of other situations. The general principles apply whenever there is a limited time is available for making decisions, and different criteria conflict with each other. Environments where such conditions could exist include: air traffic control, air defense system, monitoring and control of the spread of epidemics, monitoring the propagation of oil spills, chemical and nuclear wastes etc. The time scales could be different, and various amounts of time may be available for different contexts. Also, priorities could be different. When these factors are properly taken into account, the model should provide a means of analyzing the situations.

CONCLUSIONS

One of the most important aspects of understanding how a human operator makes decisions in situations involving multiple, possibly conflicting criteria, is to develop a good experimental paradigm. Such a paradigm has been developed. The model structure has been formulated. Possible heuristics that might be useful for the model are given.

These form the basic steps that are essential for the mathematical modeling.

Experiments have been conducted. The results are being analyzed to determine what strategies and heuristics the human might have used for the decision making problem. A detailed model structure is being worked out. The mathematical model is expected to provide results that match what is observed in the experiments. Modifications and refinements of the mathematical model may be necessary for a good match with the experimental results.

As indicated earlier, the problem considered here is part of a much bigger problem, viz. modeling of multi-operator systems. The current modeling effort is expected to lead directly and naturally into the bigger and more complex problem of supervisory control with a number of interacting entities.

ACKNOWLEDGEMENT

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A MODEL FOR HUMAN ATTENTION ALLOCATION STRATEGIES IN SITUATIONS WITH COMPETING CRITERIA

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ABSTRACT

In the operation of certain supervisory control systems, decisions must be made in a limited amount of time, and various performance criteria conflict with each other. Proper scheduling of tasks and appropriate allocation of resources are necessary for optimal performance, and in some instances, for overall safety. Conditions may prevail where it is usually not clear when different tasks could be performed. An experimental paradigm has been developed to study how the human monitor operates in such situations. The scenario used is similar to monitoring the spread of forest fires, and timely identification of threatening conditions. Experiments have been conducted based on the above mentioned paradigm. A model based on Pareto Optimality and Fuzzy Set theory has been developed for the human operator. Results of the experiments are described, and their implications for the model are discussed.

INTRODUCTION

In supervisory control where more than a single operator is involved, proper coordination is necessary for successful operation. Allocation of various functions to different operators is not usually clearly defined. At any time, depending upon the relative workload levels, one of the operators jointly responsible will perform an operation. Computers when working with the human can also be used to perform some of the functions.

A number of systems may compete for attention, and/or a number of performance criteria may conflict with each other. The criteria could differ from each other, and cannot simply be added to obtain a single performance index. Since the operator wants to optimize all the elements of the vector, the appropriate solution would be to find the Pareto optimal set of solutions. From this a single preferred solution is found by the use of heuristics and/or other relevant information. An experimental paradigm has been developed to study this situation. Efforts are being made to model the human's decision making behavior. Details of the experiment and the model are given in the following sections.

DETAILS OF AN EXPERIMENTAL PARADIGM

A typical situation considered here is the monitoring of the propagation of forest fires (Figure 1). The main features are the points at which fires have originated ("sites"), from which fires could spread to other areas in the forest. Certain areas are more valuable than others, for example, due to housing. These are called Protected Zones (PZ) and are indicated as circular arcs. The operator must determine from the information displayed whether the sites pose a threat to PZ. Time available to make this decision is limited.
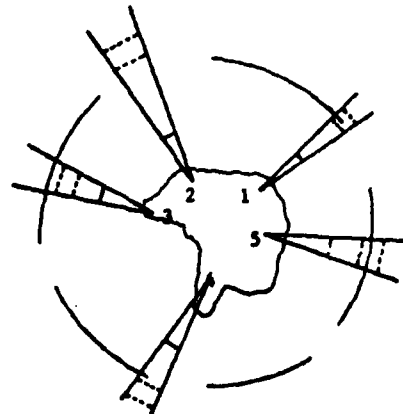

Fig. 1. Threat assessment scenario

The angular envelope for the path is indicated by a fan. It provides the 95% confidence interval for the path. The confidence interval for range is indicated by the dotted lines. The envelopes displayed are based on information available at the time the display was originally drawn. As time progresses more accurate information becomes available. The operator can ask for more information concerning any particular site at any time.

A line perpendicular to the center line of the fan gives an indication of the estimated position of the fire-front. This line is continuously updated, based on the assumption that the velocity of the front is known. The front position line moves

along the center line corresponding to the last update. This line is the only direct indication of the elapsed time. The operator gets an estimate of the remaining time from this line.

At any point in time the operator can decide if a particular site is a threat or not a threat, or can continue to monitor in the hope of obtaining more reliable information later. Since the initial information is rather crude, the rate of improvement in the quality of information is greater in the beginning.

At the beginning of the trial fires start from all five sites. The subject can update any site by typing the site number. (During updates the display is frozen for 5 seconds. In a real life situation, updating information takes some time. This reflects processes such as calling up a source of information, obtaining relevant information, processing it, and updating the display.) A message appears indicating that the requested site is being updated, and after 5 seconds, the confidence intervals are updated. When the nature of threat is identified for a site, that site is removed from the display. The experiment proceeds until all the sites have been identified or until the pre-determined time limit, whichever occurs first.

The experiment has been run in real time on a PDP 11/34 computer using the VT11 Graphics system. Initial training runs were conducted for a week to familiarize the subjects with the experiment. The subjects were encouraged to avoid making errors. A score based on the correctness of the decision concerning threat and the quickness in making the correct decision was calculated for each site. The score for a site is the time remaining at the time the decision was made. At the end, the display was redrawn to indicate the final configurations of the confidence intervals, and the scores were displayed. Incorrect identifications were shown by flashing the confidence intervals and giving zero scores. This feedback was also provided during the data runs. Details can be found in [1].

OUTLINE FOR THE MODEL

The information the operator has about the system can be divided into two main categories. One is the information concerning the Predicted End Point (PEP) at which the fire is extinguished. The PEP is shown by the width of the fan and the dotted lines indicating the range. In addition, an indication of the actual range of the fire is available from the front position line. The other information is the perceived probability of damage to the protected zone, p_d, given by the relative size of the area of overlap of the PZ and the confidence interval.

Control action consists of determining which site to investigate at any particular time. This could be done by scheduling two or more sites to be investigated consecutively. At any time, the human might possibly be ranking the various sites in

order of importance as potential threats and decide on the appropriate action. The number of sites competing for action as well as the time remaining will influence the control.

To decide the nature of the threat, the human estimates a number of quantities, such as the time remaining, positions of the fire-fronts, and the regions of uncertainty. The estimation problem is rather difficult because the operator has no control over the fires' propagation. When the uncertainty envelopes are updated, the information gained could be used to identify parameters of the human's model. The parameters thus identified could be used to estimate the variables between updates.

A set of alternative solutions is generated based on available information. Heuristics and other information concerning the threat assessment problem are formalized using fuzzy set theory. Fuzzy relationships developed from these are used to choose a single alternative from this set. When a decision is made concerning threat or when the operator is uncertain, and after information updates the cycle restarts. Detailed structures are being pursued.

Appropriate "desirability indices" must be associated with various controls that form the Pareto optimal set. Rules and heuristics that might be used by the human need to be identified for this purpose. Examples of some possible heuristics are given below. More can be found in [1].

1. Do not ask for information from the same site consecutively, unless that site could be eliminated from further consideration.
2. If p_d for site i is closer to p_{hi}, and p_d for site j is closer to p_{lo}, choose site i (potential threat is more important than a non-threat).

These rules are being tested by matching the model results with the experimental results. Unlike the direct problem where a known set of heuristics are used in fuzzy relationships, we need to identify proper heuristics and strategies by matching results.

EXPERIMENTAL RESULTS AND IMPLICATIONS FOR MODELING

Experiments have recently been completed. The results are being analyzed. Only the preliminary results are given here. It was observed that the subjects cycled through the sites in a more or less sequential order when a lot of time was available. After about two or three cycles, the subjects started investigating specific sites. Easy identifications were completed before going on to more difficult or uncertain sites. Difficult sites required more updates. In most cases, the subjects had a tendency to identify the uncertain sites with p_d near 0.5 as threats.

Some subjects declared a site a threat if, after an update, the fan moved towards a Protected Zone. They might be using some form of a predictor to

~~trapocate the PEP. The driving noise charac-
teristics for the predictor could be dependent on
the motion of the fan during the last update.

The subjects updated a site prior to the decision
concerning threat. Sites with p_d near 0.5 were
more difficult to classify than those with 0.0 or
1.0. After sessions with relatively large number
of errors in classification, the subjects were
found to take more time and make smaller number of
errors. This could perhaps be accounted for in
the model by changes in thresholds and/or the ap-
propriate descriptive parameters of the membership
functions.

It appears that there are two distinct phases in
the operation. The first phase consists of at-
tempts to reduce the uncertainties associated with
all the sites to a sufficiently low level. In the
second phase, sites are chosen for interrogation
and classification. It is during this phase that
the human generates a set of alternatives from
which a single site is chosen for update. The
phases could be labeled as (1) Uncertainty Reduc-
tion (UR) and (2) Threat Classification (TC).

During the first phase, the most popular scheme ap-
pears to be sequential updates of sites. A cru-
cial point in the development of the model is the
determination of when the human switches to the TC
phase. This is obviously a function of the time
remaining, as well as various thresholds and rela-
tive values of perceived probabilities of damage.
Detailed analysis of results is expected to pro-
vide more insight into this phase.

In the TC phase, the sites could be grouped into
three classes. The most difficult are the ones
with p_d around 0.5, with decreasing order of dif-
ficulty, the other two classes are: (0.25,0.75)
and (0.0,1.0). Fuzzy set membership functions
that depend on probability should thus be symmetr-
ical about 0.5. This classification along with
certain thresholds could be used to find the Pare-
to optimal set. Heuristics characterized by ap-
propriate fuzzy rules and relationships could then
be used to choose one particular site for investi-
gation.

A number of alternatives are possible to accom-
plish the selection of a site for update. The
rules could be individually used to evaluate
membership function values. For any site, the ap-
propriate value for the desirability index could
be chosen either (i) by using the highest member-
ship function value, or (ii) by using a weighted
function of a hierarchical ordering between rules.
Another alternative is to develop and/or identify
various fuzzy relationships that would provide the
desirability function value. Relative importance
of various rules could form the basis for these
relationships. The site having the highest value
could then be interrogated. Parameters in the
rules could be changed to reflect individual
differences between operators, and trial-to-trial
variation among operators.

ALTERNATE MODELS

An attractive alternative for modeling appears to
be the use of Semi-Markov Decision Processes [2].
In addition to the number of sites, a state for
monitoring, and an absorbing state corresponding
to site identification could be used. The main
problem here is the determination of the transi-
tion probabilities. These are time varying, and
there appears to be no method to evaluate these
probabilities. They could vary depending on the
number of sites remaining, and after each update.
Positions of fans relative to the protected zones
might also have a direct influence on the transi-
tion probabilities. This method is being studied.

Yet another method is the develop a computer model
using LISP or other symbol manipulation languages.
Programs in LISP seem to be particularly attrac-
tive since various relations and hierarchical ord-
erings between rules could be easily programmed.
This and other artificial intelligence techniques
such as *Production Systems* will be explored in de-
tail. Incorporating the history (configuration
changes with updates) is relatively straightfor-
ward in these approaches.

CONCLUSIONS

An important aspect of understanding how a human
operator makes decisions in situations involving
multiple, possibly conflicting criteria, is to
develop a good experimental paradigm. Such a
paradigm has been developed. The model structure
has been formulated. These form the basic steps
that are essential for mathematical modeling.

Experiments have been conducted. The results are
being analyzed to determine what strategies and
heuristics the human might have used for decision
making. This should help identify the useful
model features. A detailed model structure is be-
ing worked out.

In addition to its use in the monitoring situation
considered here, the model could be useful in a
number of other situations. The general princi-
ples apply whenever there is a limited time avail-
able for making decisions, different criteria con-
flict with each other, and priorities are dif-
ferent for various subsystems.

ACKNOWLEDGEMENT

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